Renewable Energy 97 (2016) 757–768

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Technoeconomic parametric analysis of PV-battery systems

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A R T I C L E I N F O

Article history:
Received 11 February 2016
Received in revised form
2 June 2016
Accepted 5 June 2016

Keywords:
Solar photovoltaic
Energy storage
Battery
Distributed generation
Decision analysis
Technoeconomic analysis

A B S T R A C T

Application of integrated PV-battery systems for off-grid locations has a history exceeding four decades. With the observed fast reduction of PV and battery system prices in recent years, however, interest in the use of PV-battery systems has notably increased even at on-grid locations. The aim of this paper is to assess the impact of various technoeconomic parameters, such as geographic location, weather condition, electricity price, feed-in tariff, PV/battery system cost, and PV/battery specifications on the economic feasibility of grid-connected PV-battery systems. For this, we have used our inhouse decision support tool for investment decision making, optimal sizing, and operation scheduling of grid-connected PV/battery system with respect to these parameters. The results show that decision on the selection of the right PV-battery system is significantly sensitive to each and every one of these parameters. Within various price scenarios that we carried out, battery shows positive impact on NPV only at low installation costs (e.g. ≤750 $/kWh). Neither the sales electricity tariff nor the feed-in tariff has alone a direct impact on the feasibility of installing a battery system. Rather, the magnitude of the difference between electricity price and feed-in tariff is the detrimental element in battery attractiveness. A case-study for Sydney, Australia, showed that at current sales/feed-in electricity tariffs, PV systems with prices of 2700 $/kW, or less, not only reach parity with the grid electricity price but also reach parity with feed-in tariff. This implies the viability of installing large PV systems merely for selling the generated electricity to the grid.

1. Introduction

With the rapid reduction in PV system prices in recent years, interest in the use of grid-connected PV generation and/or battery systems has notably increased. Traditionally, PV systems have been used in two configurations, grid-connected without battery and off-grid (stand-alone) with battery (Fig. 1). Fig. 2 illustrates the key challenge of PV technology, even at infinitely high system sizes, to supply the full electricity demand of a typical household customer. PV systems cannot supply electricity demand outside daylight times. In off-grid applications, therefore, electricity storage becomes an inseparable part of PV generation (ignoring cost issues), to ensure higher power reliability.

According to the International Energy Agency, "as PV matures into mainstream technology, grid integration and management and energy storage become key issues" [1]. This necessity has triggered the term "community energy storage" [2,3], reflecting the need for electricity storage at the demand-side. This translates into the introduction of a third configuration, the grid-connected PV-battery system (see Fig. 3).

Initial efforts in the sizing of integrated PV-battery systems focused mainly on off-grid and rural areas, using approximate methods which resulted in over-sized or under-sized systems [4]. Later, iso-reliability curves were introduced by Egido and Lorenzo [5] which is based on developing numerous graphs of PV-storage sizes, each at a certain reliability value. A good review on the iso-reliability method and a rule-of-thumb approximation on that basis is given by Egido and Lorenzo [5]. As computers emerged, PV-battery sizing models also improved in rigor. For instance, instead of daily average solar irradiation or load data, real historical time series were used [6,7], or characteristic equations were used instead of simple efficiency values for PV panel, battery, inverters [8], etc.

With the global attention to the PV transformation within the last decade, there has been increasing interest in linking PV and/or battery systems with the electricity market and a need to develop an optimal operation schedule. Lu and Shahidehpour [9] developed a short-term scheduling model for battery use in a grid-connected

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http://dx.doi.org/10.1016/j.renene.2016.06.010

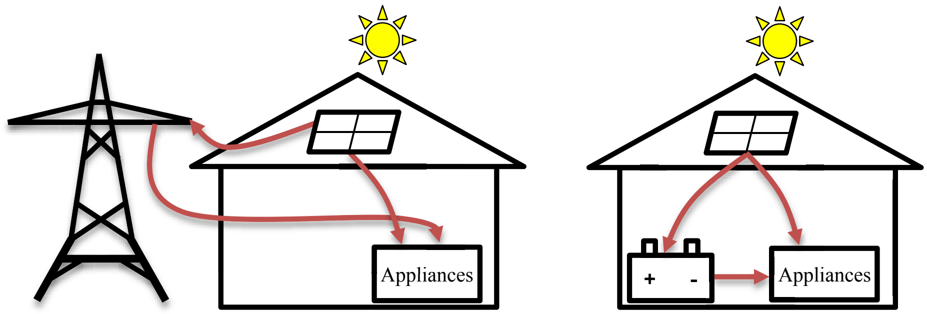

Fig. 1. Schematic of two DG configurations: grid-connected PV (left) and off-grid (stand-alone) PV with storage (right).

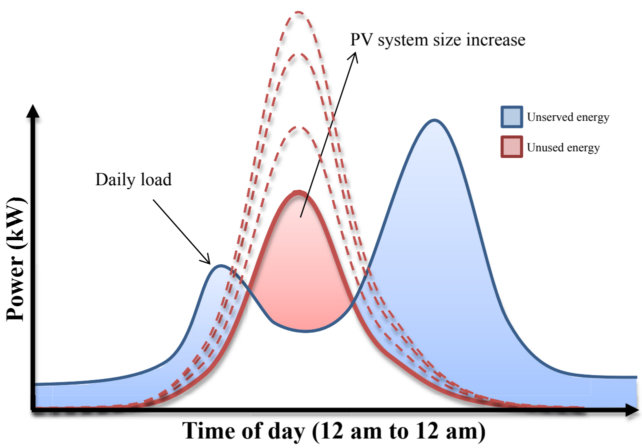

Fig. 2. The PV challenge: even a very large PV system cannot meet the full load of a typical household.

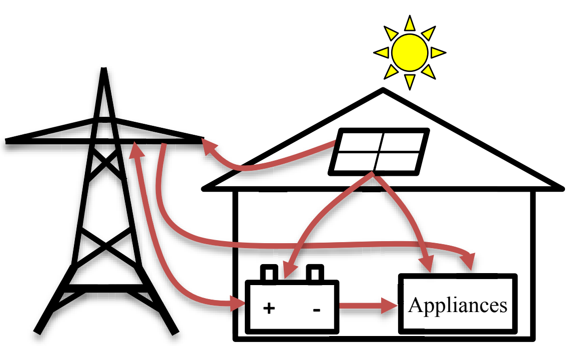

Fig. 3. Illustration of a grid-connected PV-battery system.

PV-battery system using a Lagrangian relaxation-based optimization algorithm to determine the hourly charge/discharge commitment of a battery in a utility grid. They used an eight-bus test system as a case study and investigated the impact of grid-connected PV-battery system on locational pricing. Kaushika et al. [10] developed a linear programming formulation for a stand-alone PV-battery system with an objective to find out the optimum combination of the number of batteries and PV modules to allow the operation of the system with zero loss of power supply probability (LPSP) or 100% reliability.

Some researchers have also used artificial intelligence techniques for sizing PV-battery systems [11]. Riffonneau et al. [12] presented a dynamic programming methodology for "day-ahead" predictive management of grid-connected PV systems with storage. The program, which also considered battery aging, successfully achieved its peak-shaving goal at minimum costs. Yu et al. [13] studied the problem of determining the size of battery storage for grid-connected PV systems. They proposed lower and upper bounds on storage size and introduced an optimization algorithm for finding the optimal battery size. They identified a unique critical value for battery size, below which the total electricity cost was high, whereas above that, increases in battery size had no impact on costs. Ratnam et al. [14] developed a framework based on quadratic programming which enabled the customer to justify expenditure on battery storage either through a least-cost option of capital investment or through choosing to utilize existing electric vehicle battery storage, if available.

Some researchers have focused on efficient operation of PV-battery systems. According to Halliday et al. [15], though PV systems account for a significant part of the initial investment in PV-battery systems, their share of lifetime capital cost (over 20 years) of the system is around one third. This is while batteries account for half of the total capital cost due to lowered expected battery lifetime as a result of inefficient battery operation (high temperatures, low SOC, etc.). As such, optimal control of battery charge/discharge (SOC) is a key component in improving the economics of the overall system. One of the earliest studies of efficient battery operation was by Appelbaum et al. [16], who developed geometrical regions on V-I characteristic graphs of solar systems for efficient charge/discharge of batteries and load control. More recently, Fragaki and Markvart [17] compared modeling and experimental data of PV-battery systems. Although their application of battery charging efficiency reduced the gap between experiment and model, they highlighted the necessity of development of a method to account for system memory effects imposed by the operation of the charge controller.

Pedram et al. [18] discussed that current homogeneous EES systems had limitations in simultaneously achieving desirable performance features such as high charge/discharge efficiency, high energy density, low cost per unit capacity, and long cycle life. As such they proposed the application of hybrid EES (HEES) systems with each EES element having strength in certain performance feature. Stadler et al. [19] developed a distributed energy resources customer adoption model (DER-CAM) based on a mixed integer optimization program. The model is capable of using various DG and storage types. Wang et al. [20] developed a dynamic programming model for integration of a residential-level HEES system for smart grid users equipped with PV power generation. The program objective was to reduce the total electricity cost over a billing period and to perform peak power shaving under arbitrary energy prices, also considering the characteristics of different types of EES elements, conversion efficiency variations of power converters, as well as the time-of-use- (ToU) dependent energy price function. They reported up to 73.9% profit improvement when